



# A Prototype Dynamics Model of Bench Blasting Design

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**Abstract:** *This paper presents the application of dynamic modelling for designing bench blasting patterns. By combining the terms of bench blasting design pattern, production planning, noise, vibration, fly rock, and estimation of drilling and blasting costs, as a decision making tool for planning bench blasting efficiency, reducing the environmental impacts of noise, vibrations, and fly rock from the bench blasting can be created.*

*The results of a prototype model can be used to design bench blasting patterns following mine production planning and are based on the theory of the bench blasting as well. The developed model is incorporated in the assessment of drilling and blasting costs, it also makes it easy to compare the results of the design in terms of the underlying model for the design of the bench blasting. Therefore, this model is one of the alternatives that can be used to support the decision making in planning of bench blasting design patterns effectively.*

**Key Words:** Bench Blasting Design / System Dynamics Model / Prototype Blasting Model

## 1. INTRODUCTION

Design and development equations of bench blasting design patterns are efficiency and progress continuing. From past to present, many empirical formulas are presented for the design of the bench blasting properly. Furthermore, the blasting equations associated with reducing the impact of noise, vibration, fly rock, and costs of drilling and blasting are closely linked. However, the lack of tools to link the various parts together, help to understand and plan effectively for the bench blasting process.

Prototype dynamics model of bench blasting design (PDMBBD) is included: firstly, equations and

design criteria for bench blasting following theory of the Drilling and Blasting of Rocks [1-3], secondly, the environmental impact control equations for controlling the impacts of noise, vibrations, and fly rock in blasting [2, 4], and finally, costs estimation from the drilling and blasting design. This model is created by Vensim, which is generally used in system dynamics modelling design [5]. The aim of PDMBBD is to help the designing of suitable bench blasting patterns, safely charge of explosive per delay, and optimum cost per production.

## 2. BENCH BLASTING DESIGN

Equations for design bench blasting patterns were developed since 1952 by Anderson and Fraenkel, next in 1955 by Pearse, then Hino (1959), Allsman (1960), Ash and Langefors (1963), Hansen (1967), Ucar and Konya (1972), Földesi, Praillet and Lopez (1980), Konya (1983), Berta, and Bruce (1985), Olofsson and Rustan (1990) [1], and Pham (2011) [6], etc. Which already have more than 18 equations until now.

In 1994 Persson, et al. [2] published the book "Rock Blasting and Explosive Engineering", C. Lopez Jimeno, et al. (1995) published "Drilling and Blasting of Rocks" [1], then "Engineering rock blasting operations" was published by Bhandari in 1997 [3].

In spite of much research work in blasting technology, no single theory or set of equation exists which can be used efficiently for blasting design in surface mining operations with different mine conditions. With the modification of established equations on the basis of data obtained from blasting fields, the optimum design parameters can be determined [7].

C. Lopez Jimeno, et al. (1995) present tables function of K factors for bench blasting design by

using 2 parameters as drill hole diameter, and compressive strength. The factors are separated into 2 groups, the small hole diameter (65-165 mm) in Table 1, and the large hole diameter (180-450 mm) in Table 2 [1].

Table 1 Design factors for small hole diameter

Design parameter (m)	Uniaxial compressive strength (MPa)			
	Low <70	Medium 70-120	Hard 120-180	Very hard >180
Burden (B)	39D	37D	35D	33D
Spacing (S)	51D	47D	43D	38D
Stemming (T)	35D	34D	32D	30D
Subdrilling (J)	10D	11D	12D	12D
Bottom charge length (Lf)	30D	35D	40D	46D

D=hole diameter (m)

Table 2 Design factors for large hole diameter

Design parameter (m)	Uniaxial compressive strength (MPa)		
	Low <70	Medium-Hard 70-180	Very hard >180
Burden (B) - ANFO - Watergel/ Emulsions	28D 38D	23D 32D	21D 30D
Spacing (S) - ANFO - Watergel/ Emulsions	33D 45D	27D 37D	24D 34D
Stemming (T)	40D	32D	25D
Subdrilling (J) - $\phi$ 180-250mm - $\phi$ 250-450mm	7-8D 5-6D		
Bottom charge length (Lf)	8-16D		

D=hole diameter (m)

Equations for calculating patterns of bench blasting are presented below [1].

Hole length  $L$  (m) can be determined by equation 1:

$$L = \frac{H}{\cos \beta} + \left(1 - \frac{\beta}{100}\right) \times J \quad (1)$$

where  $H$  is the bench height (m),  $\beta$  is an angle with vertical line (degree), and  $J$  is subdrilling (m).

Volume of broken rock per hole  $VR$  (m<sup>3</sup>) can be determined by equation 2:

$$VR = B \times S \times \frac{H}{\cos \beta} \quad (2)$$

where  $B$  is burden (m), and  $S$  is spacing (m).

Yield of broken rock  $RA$  (m<sup>3</sup>/m) can be determined by equation 3:

$$RA = \frac{VR}{L} \quad (3)$$

Powder factor  $PF$  (kg/m<sup>3</sup>) can be determined by equation 4:

$$PF = \frac{Q_b}{VR} \quad (4)$$

where  $Q_b$  is blasthole charge (kg).

Environmental impacts of bench blasting are important factors. The main impacts are noise, vibration, and fly rock from blasting.

The affect of noise depends upon the pressure of air blast which is estimated by equation 5 [2]:

$$db = 20 \times \log \left( \frac{P}{P_0} \right) \quad (5)$$

where  $db$  is scale level of noise (decibel),  $P$  is air pressure from the blast (bar), and  $P_0$  is a reference pressure equal  $2 \times 10^{-10}$  (bar).

Air pressure from blast  $P$  (bar) can be estimated by equation 6:

$$P = 0.7 \left( \frac{W^{\frac{1}{3}}}{R} \right) \quad (6)$$

where  $W$  is weight of explosive (kg) and  $R$  is the distance between the blasting area and the measuring area (m).

The affect of ground vibration depends upon its magnitude and frequency which are based on the blast design, blasting pattern, explosive properties, local geology, structural discontinuities, etc [4].

Many vibration predictor equations are presented from 1962 to present. The famous vibration predictor equations are Duvall et al. (1962) (USBM), Ambraseys et al. (1968), Langefors & Kihlstrom (1978), Ghosh et al. (1983), etc.

In 2004, Rajesh Rai and T N Singh [4] present new vibration predictor equation and compared it to other predictor equations in the past. The result in comparison found that the new equation gives better accuracy result than other equations following equation 7:

$$V = K \cdot R^{-B} \cdot Q_{max}^A \cdot e^{-\alpha R} \quad (7)$$

where  $V$  is peak particle velocity (mm/s),  $K$ ,  $A$ ,  $B$  and  $\alpha$  are site constants,  $R$  is the distance between the blasting area and the measuring area (m),  $Q_{max}$  is a maximum charge per delay (kg).

The site constants to be determined by regression analysis, for some type of rocks are shown in Table 3.

Table 3 List of vibration predictor constants [4]

Materials	$K$	$B$	$A$	$\alpha$	$r$
Limestone*	82.701	1.197	0.802	$1.00 \times 10^{-3}$	0.856
Dolomite	275.39	1.463	0.809	$1.09 \times 10^{-3}$	0.928
Sandstone	713.23	-1.463	0.607	$1.47 \times 10^{-5}$	0.868

$r$  = correlation coefficient;

\* default conditions used in PDMBBD

From equation 7, it is rearranged for finding  $Q_{max}$  in equation 8:

$$Q_{max} = \left[ \frac{V}{K \times R^{-B} \times e^{-\alpha R}} \right]^{\frac{1}{A}} \quad (8)$$

The affect of the maximum distance of fly rock  $R_{max}$  (m) and the maximum size of bolder  $\phi$  (m) can be determined by equation 9 and 10 respectively:

$$R_{\max} = 260 \times d^{\frac{2}{3}} \quad (9)$$

$$\phi = 0.1 \times d^{\frac{2}{3}} \quad (10)$$

where  $d$  is the hole diameter (inch).

### 3. SYSTEM DYNAMICS

System dynamics is an approach to understanding the behavior of complex systems over time. It is a powerful methodology and computer simulation modelling technique for understanding, and discussing complex issues and problems [8].

System dynamics which founded by Prof. J.W. Forrester in 1950 [9], is a theory of system structure and a set of tools for representing the structure of complex systems and analysing their dynamic behaviour. In Fig 1 shows the generic structures for creating a dynamics model.

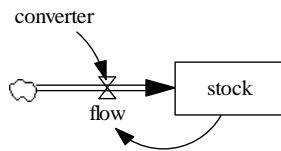


Fig 1 Generic structure of system dynamics model

### 4. METHODOLOGY

Because of complex variables and many equations in blasting which some variables change others change follows. So with this technique, the variables are analyzed and connected for respondents when some variables changed.

In this paper, model structures and equations are created in Vensim software [5] following system dynamics theory. The simple flowchart of PDMBBD is presented in Fig 2.

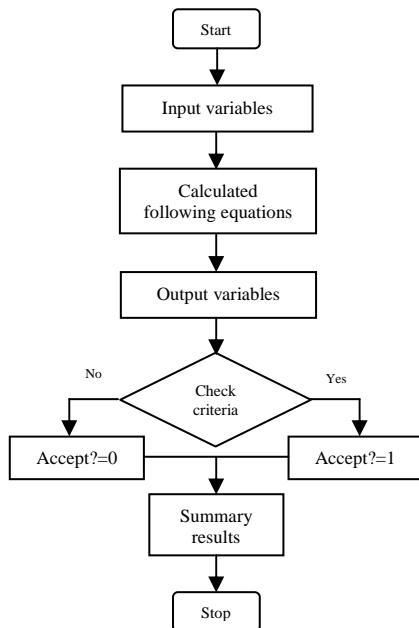


Fig. 2 Simple flowchart of PDMBBD

### 5. LIST OF VARIABLES

There are 25 main input variables, 33 main output variables, and 10 main criteria variables in Table 4, 5 and 6 respectively. However, in the structure of the model, it is necessary to add more variables than are shown in the table below, such as function for selecting values of coefficient factors in the equations, the converter variables for correcting unit of variables, etc.

Every variable is defined as a symbol in a short description which will be used in the model structure.

Table 4 List of main input variables in PDMBBD

Name	Symbol	Value	Ref
1. A value of ground vibration equation	A	0.802 (Limestone)	[4]
2. Alpha value of ground vibration equation	Alpha	$1.0 \times 10^{-3}$ (Limestone)	[4]
3. B value of ground vibration equation	B	1.197 (Limestone)	[4]
4. Blast hole inclination (degree)	BHI	0 (Vertical)	*
5. Blasting production planning (tons/day)	BPP	1,000-10,000	Sc
6. Cap per hole (cap/hole)	CH	1	*
7. Compressive Strength of rock (Mpa)	CS	50-200	Sc
8. Hole Diameter (mm)	D	50-400	Sc
9. Density of ANFO (kg/cu.m.)	DANFO	800 (Loose)	[3]
10. Density of Fuel Oil (kg/Liter)	DFO	0.8	[2]
8. Density of High Explosive (kg/cu.m.)	DHE	1,200 (Emulsion)	[2]
9. Density of materials (kg/cu.m.)	DM	2,400 (Limestone)	[2]
10. Input drilling rate (m/min)	ID	0.35	[2]
11. Input Bench High (m)	IH	15 (Max.)	[1]
12. K value of ground vibration equation	K	82.701	[4]
13. Coefficient of maximum distance of fly rock	Kfr	260	[2]
14. Coefficient of maximum diameter of fly rock	Kfs	0.1	[2]
15. Option type of main explosive (0=ANFO, 1=Watergel/Emulsion)	OME	0	*
16. Reference Pressure (bar)	P0	$2.0 \times 10^{-10}$	[2]
17. Peak particle velocity (mm/s)	PPV	8 (DIN 4150)	[2]
18. Distance between blasting area and measuring area (m)	R	500-1,500	Sc
19. Ratio of AN (%)	RAN	94.5	[3]
20. Unit cost per kg of AN (euro/kg)	UAN	0.42	q
21. Unit cost of Cap (euro/cap)	UC	0.62 (Electric cap)	q
22. Unit cost of drilling (euro/hr)	UD	35	*
23. Unit cost per Liter of Fuel Oil (euro/Liter)	UFO	0.67	q
24. Cost of High Explosive (euro/kg)	UHE	2.29	q
25. Work time for drilling (hr/day)	WTD	8	*

\* = Assumption value;

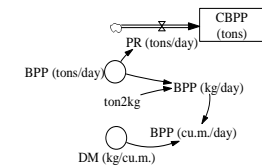
Sc = variables use for simulation in scenarios.

q = in the query

Name	Symbol	Name	Symbol
1. Cumulative blasting production (tons)	CBPP	2. Burden (m)	B
3. Spacing (m)	S	4. Stemming (m)	T
5. Subdrilling (m)	J	6. Bottom charge (m)	Lf
7. Breakage volume per hole (cu.m.)	VR	8. Breakage weight per hole (tons)	BWH
9. Weight of ANFO (kg)	Qc	10. Total Weight of Explosive (kg)	Qb
11. Weight of High Explosive (kg)	Qf	12. Number of holes to drill (hole/day)	NH
13. Time for drilling (hr/day)	TD	14. The number of drilling machine required	NDM
15. Cost of High Explosive (euro/day)	CHE	16. Cost of AN (euro)	CAN
17. Cost of ANFO (euro/day)	CANFO	18. Cost of Fuel Oil (euro)	CFO
19. Cost of Caps (euro/day)	CC	20. Total cost of explosive (euro/day)	TCE
21. Total cost of Blasting (euro/day)	TCB	22. Total cost of drilling (euro/day)	TCD
23. Total cost of drilling and blasting (euro/day)	TCDB	24. Cumulative cost of drilling and blasting (euro)	CCDB
25. Cost per production (euro/ton)	CPP	26. Q max (kg)	Qm
27. Maximum hole per delay (hole)	MHpD	28. Maximum distance of Fly Rock (m)	MDFR
29. Noise from Blast (dB)	db	30. Estimate air pressure from the blast (bar)	P
31. Fly rock diameter size (m)	FRD	32. Yield of broken rock (m <sup>3</sup> /m)	RA
33. Decision making for all blasting design conditions (1=yes, 0=no)	FDM		

Model structures of PDMBBD are separated into 6 sub-models.

- In the model structure, the input variables are shown in ○ symbol, the output variables are shown in normal text, the criteria variables are shown in ⬡ symbol, the cumulative variables are shown in □ symbol, the rate variables are shown in ⚡ symbol, and all of the sub-models are connected by variables with < > symbol.



Name	Symbol	Recommended	Ref.
1. H/D ratio	H/D	> 60	[3]
2. H/B ratio	H/B	>= 3	[1]
3. L/D ratio	L/D	>60	[1]
4. S/B ratio	S/B	1-1.4	[1]
5. T/B ratio	T/B	0.7-1.5	[3]
6. J/B ratio	J/B	0.1-0.5	[1]
7. Lf/B ratio	Lf/B	0.3-1.3	[1]
8. Powder factor (kg/m <sup>3</sup> )	PF	0.25-0.55 (small hole) 0.25-1.20 (large hole)	[1]
9. Specific charge (kg/ton)	SC	0.1-0.4	[3]
10. Hole inclination (degree)	BHI	0-20	[3]

Fig. 5 Sub-model: Environmental Control

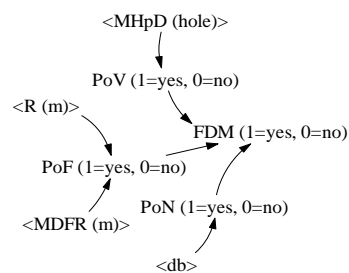
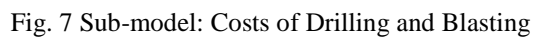
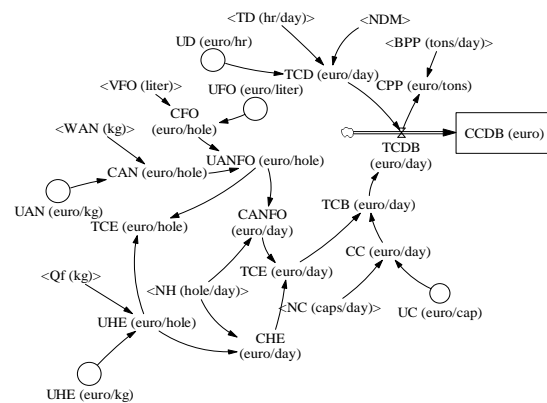
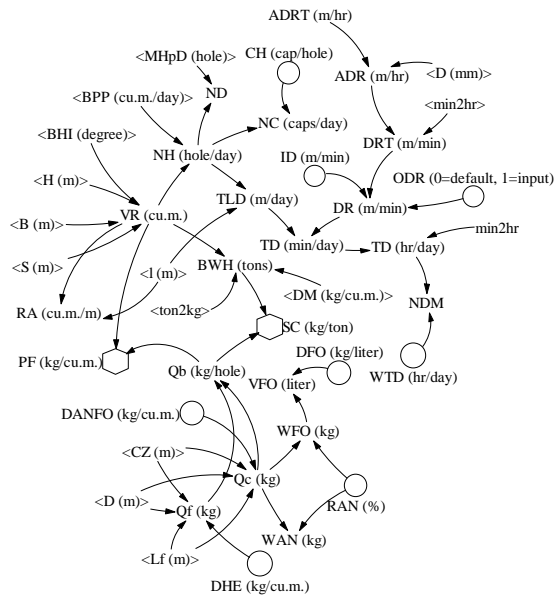
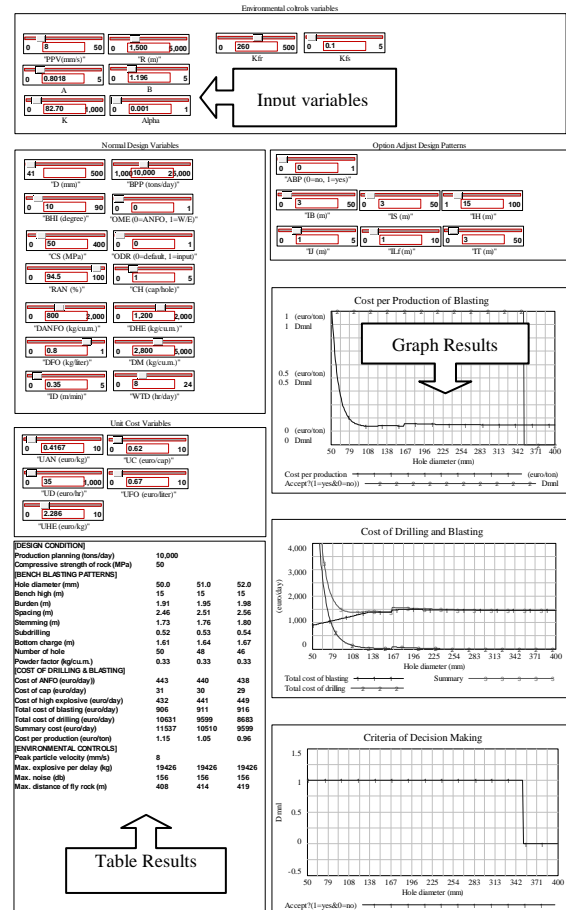


Fig. 8 Sub-model: Decision Making

In Fig. 9, shows the main input variables, the graphs of main output variables, and the table of all important calculation variable results. It is possible for the user to change any variables, to get results, and help to compare results in each scenario at the same time.

Therefore, the user can make the suitable decision by comparison result in each scenario, changed site conditions and decide the following output of result by themselves.



## 7. MODEL SCENARIOS

From the list of main input variables in PDMBBD (Table 4), Three main variables are taken into account to create sample simulation scenarios, including blasting productions planning (BPP), compressive strength of rock (CS), and the distance between the blasting area to the measuring area (R). The aim of these sample simulations is to find the suitable hole diameter (D) which make minimum cost per production (CPP) possible.

There are 27 scenarios created in the following Table 7. In every scenario, hole diameter varies between 50-400 mm for finding the suitable result.

Table 7 Metrix variables for scenario simulation

Variables	Value1	Value2	Value3
D (mm)	Vary between 50-400 mm		
BPP (tons/day) (Short symbol)	1,000 (B1)	5,000 (B5)	10,000 (B10)
CS (MPa) (Short symbol)	50 (C5)	100 (C10)	200 (C20)
R (m) (Short symbol)	500 (R5)	1,000 (R10)	1,500 (R15)

The criteria for the selected suitable result is not only the minimum of cost per production (CPP), but also the environmental control, including vibration (PPV), noise (db) and fly rock (MDFR). These criteria are shown in Table 8.

Table 8 Environmental control criteria

Name	PPV (mm/s)	db (decibel)	MDFR (m)
Criteria value	8 [2]	<172 [2]	<R

## 8. SIMULATION RESULTS

From 27 scenarios, minimum cost per production CPP (euro/ton) and the suitable hole diameter D (mm) are determined in Table 9.

Table 9 Suitable hole diameter of 27 scenarios

Scenario Code	Group	Suitable hole diameter (mm)	Estimated cost per production (euro/ton)
1. B1C5R5	G9	(67 <sup>A</sup> )	(0.147)
2. B1C5R10		81	0.136
3. B1C5R15		81	0.136
4. B1C10R5	G8	(67 <sup>A</sup> )	(0.193)
5. B1C10R10		81	0.179
6. B1C10R15		81	0.179
7. B1C20R5	G7	(67 <sup>A</sup> )	(0.289)
8. B1C20R10		81	0.265
9. B1C20R15		81	0.265
10. B5C5R5	G6	(67 <sup>A</sup> )	(0.270)
11. B5C5R10		102	0.154
12. B5C5R15		102	0.154
13. B5C10R5	G5	(67 <sup>A</sup> )	(0.363)
14. B5C10R10		102	0.204
15. B5C10R15		102	0.204
16. B5C20R5	G4	(67 <sup>A</sup> )	(0.573)
17. B5C20R10		102	0.308
18. B5C20R15		102	0.308
19. B10C5R5	G3	(67 <sup>A</sup> )	(0.423)
20. B10C5R10		113	0.164
21. B10C5R15		113	0.164
22. B10C10R5	G2	(67 <sup>A</sup> )	(0.575)
23. B10C10R10		113	0.218
24. B10C10R15		113	0.218
25. B10C20R5	G1	(67 <sup>A</sup> )	(0.927)
26. B10C20R10		113	0.330
27. B10C20R15		113	0.330

<sup>A</sup> maximum hole diameter allowing for the short distance between the blasting area to the measuring area.

From Table 9, results of cost per production and suitable hole diameter do not change with distance between the blasting area and the measuring area (R). Therefore, results from the simulation can be arranged in 9 groups by blasting production planning (BPP) and compressive strength (CS) which is shown in Fig 10.

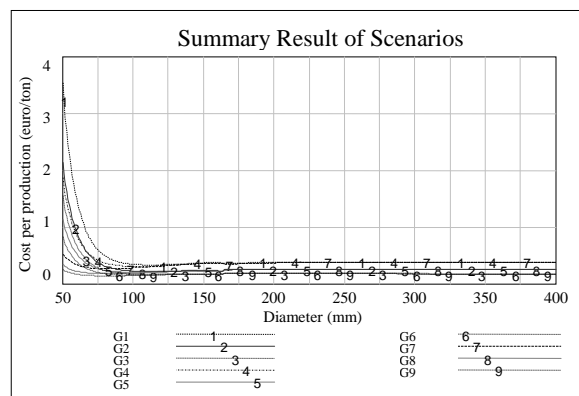


Fig. 10 Summary result of scenarios

Results of sample simulation scenarios show relationship comparison between each variable in the graph and the table. It helps to understand the variables involved such as, the suitable hole diameter for minimum cost per production (CPP) are increased following the blasting production planning (BPP). The cost per production (CPP) is directly related with compressive strength of rock (CS). Moreover, the distance between the blasting area and the measuring area (R) is an important criteria for environmental control, specifically in case of short distance, etc.

## 9. CONCLUSIONS

A prototype dynamics model of bench blasting design shows the calculation results in many scenarios automatically when changed input variables. Thus, It can be one of the alternative tools which helps to design bench blasting patterns for an initial design or the adjustment of previous pattern. Moreover, the PDMBBD can make the cumulative value of total cost of drilling and blasting (CCDB) and cumulative blasting production planning (CBPP) per day in terms of month or year by changing the period of simulation time. Thus, it is a flexible and easy tool to design bench blasting patterns.

However, this model is a prototype model. It needs to be developed and more variables need to be added such as the condition of the rock mass, further more alternative equations, or other type of blasting. In addition, an adjustment and update value of input variables related to the site conditions before used are necessary.

In the future, PDMBBD can be extended and included another process of mining such as loading and transportation, crushing and processing which will lead to the more useful tool for decision making.

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